A Space Communications Study

Progress Report

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Introduction

This progress report summarizes the work done from 15 September 1965 to 15 March 1966 in the area of Space Communications.

The problems considered during this period were:

1. Intermodulation Distortion in a Phase Locked Loop,
2. Error rates obtained in Demodulating Frequency Shift Keyed Signals using an FM Discriminator,
3. The Response of an FM Discriminator to a Fading FM Signal,
4. Optimum Estimators,
5. An Intensive Study of the Threshold Performance of the Phase Locked Loop and Frequency Demodulator Using Feedback,
6. Digital Communications Employing an Information Feedback Link,
7. An exact analysis of distortion in pulse count type FM detectors,
8. Development of theory for and the construction of a bread-board model of a wideband, low distortion FM generator using digital and diode waveshaping techniques,
9. Studies of both quasi-static and dynamic distortions in Foster Seely discriminators.
10. Intermodulation effects in a multichannel FM signal transmitted via a simulated time dispersive channel,
11. Theoretical and experimental study of a "frequency locked loop" FM detector in the presence of fading and noise,

12. Demodulation of Signals Transmitted through Fading Channels,
13. Intermodulation distortion and transient effects in fast AGC systems.

Report

1. Intermodulation Distortion in a Phase Locked Loop.

Above threshold, the Phase Locked Loop is often considered to behave linearly, and the output signal to noise ratio is

$$(SNR)_{OUT} = 3\beta^2 (\beta+1) (CNR)_{IN} \tag{1}$$

This equation assumes the presence of only one sinusoidal modulating signal.

In Space applications, one often transmits many information bearing signals simultaneously, by assigning each signal a subcarrier and frequency modulating the combined signal. The resulting modulating signal is usually wideband and "noiselike."

The "beating" together of these signals due to the nonlinearities present in the Phase Locked Loop results in Intermodulation Distortion. The Intermodulation Distortion in the Phase Locked Loop due to the system nonlinearities has been calculated. A Phase Locked Loop was constructed and the Intermodulation Distortion was measured. It was found that the major contributor to the Intermodulation Distortion was the Phase Detector, the Distortion caused by the Voltage Controlled Oscillator being 20 db less than that caused by the Phase Detector.

Figure 1 shows the Intermodulation Distortion for a Phase Locked Loop as a function of rms frequency deviation. As expected, an increase in deviation causes an increased distortion.

2. Error Rates Using an FM Discriminator

Digital information is often transmitted from a satellite to earth using frequency shift keying (FSK).

Figure 2 shows three possible signals to be transmitted, alternating ones and zeros, two ones alternating with two zeros, and three ones alternating with three zeros. A general signal is composed of combinations of these signals. The information is first frequency band-limited and then frequency modulated.

The received signal is added to the input noise in the receiver, and then passed through an FM Discriminator as shown in figure 3. The demodulated output is filtered and sampled. If the sampled voltage is positive a plus one is assumed, if a negative voltage appears a minus one is assumed to have been transmitted.

If the discriminator were linear the error rate after demodulation could be simply calculated using standard gaussian noise-matched filter techniques. The discriminator is, however, a nonlinear device, even above "threshold." When the input noise satisfies certain conditions spikes occur at the discriminator output. These spikes have an area of 2π radians and can be approximated by an impulse function which is filtered before sampling as shown.

In figure 2 we saw that the area of a bit was proportional to ΔT radians. Figure 4 shows the variation of the errors/sec as a function of ΔT. The carrier to noise ratio (CNR) is a parameter. The increase in error rate at intermediate values of ΔT is due to the spikes. At large and small values of ΔT the error rate is determined by the gaussian noise. We see from this figure that one can transmit a signal having less energy per bit and make less errors/sec. Figure 4 also shows the close correlation between theoretical and experimental results.

Making use of our knowledge of the spike characteristics we are currently trying to reduce the errors due to spikes by sensing when a spike appears. So far error rates have been able to be reduced by a factor of 5.

3. <u>The Response of an FM Discriminator to a Fading FM Signal</u>

Communication over a Fading channel using FM Signals has been used for many years. Until now, however, no analysis was available to determine the output signal to noise ratio (SNR) as a function of the CNR and the depth of fade. A theoretical analysis has been performed and an analytical expression obtained which yields the output SNR as a function of CNR, depth of fade, fading rate, and the other system parameters.

Figure 5 shows the output SNR-CNR characteristic for a 20db and a 40db fade. Note, that the effect of fading is to increase threshold, and to limit the maximum SNR possible. (When no additive noise is present, the jitter due to the fade results in an effective output noise power).

Error rates have also been calculated and experimental measurements are currently being taken.

4. Optimum Estimators

A Bayes Estimator is one which minimizes the average risk for a particular cost function. If the cost function is an infinite well (an impulse), a maximum likelihood estimator results. If the cost function has a mean square characteristic, the result is a least mean square estimator. These estimators are important since they are "optimum" estimators, and suboptimum estimators such as the Phase Locked Loop, Frequency Demodulator Using Feedback and the FM Discriminator have lower output SNR and poorer Thresholds.

Circuit representations for the Maximum Likelihood Estimator have been obtained by D. Youla, M. Schwartz and R. L. Pickholtz of the Polytechnic Institute of Brooklyn. Circuit representations for the least mean square estimator have been obtained by Schilling and Abbate for a constant channel. Schilling and Crepeau are presently obtaining circuit representations for least mean square estimators of an FM Signal passed through a fading channel.

In addition, a program has been initiated to determine how much higher is the SNR and how much lower the threshold of an optimum estimator is compared to that of a suboptimum estimator such as the Phase Locked Loop.

5. An Intensive Study of The Threshold Performance of the Phase Locked Loop and Frequency Demodulator Using Feedback

Phase Locked Loops have been constructed and a theory developed to predict output SNR-input CNR characteristics. Figure 6 shows the Phase Locked Loop characteristic. Notice that a 0db to 2db threshold is achieved experimentally.

Similar theoretical and experimental results have been obtained for the Frequency Demodulator Using Feedback. These are shown in Figure 7 which again shows experimentally obtained thresholds of 0db to 2db. A comparison of the thresholds of each device as a function of the modulation index is shown in figure 8. The symbol β is the modulation index while β^1 is the estimate of the modulation index. Notice that when the modulation index is small, the phase locked loop has a lower threshold than the frequency Demodulator Using Feedback.

This work is continuing in the following ways:

a. The effect of adding delay to the phase locked loop is being investigated. This will simulate the effect of adding spurious poles to the loop.

b. The use of a Frequency Demodulator Using Feedback with a Phase Locked Loop in the Loop, instead of a discriminator, is being studied. This should reduce the threshold of the FMFB at low modulation indices.

c. An Analog and Digital computer study to precisely determine the effect of each parameter on the threshold performance is being made.

6. <u>Digital Communications Employing an Information Feedback Link</u>

This problem concerns itself with the transmission of digital information from a source having low average power capability (as a satellite) to a receiver having the capability of high power transmission (such as a ground station).

The first part of the problem assumes that the received information is coded in M level pulse amplitude modulation. The receiver has the option of making a decision or asking for a repeat. (This repeat can be made after completing the message, or in an orbiting satellite at the beginning of its next transmission). The request for repeat made by the ground station has an order of magnitude lower probability of error than the transmitted signal if the receiving station transmitter has more than 1db greater transmitting power capability.

Consider that the receiver is unsure if the k or k + 1st level was transmitted. It asks for a repeat by transmitting the kth level. If the kth level is correct, the satellite transmitter transmits a -1, if the k + 1st level was originally transmitted, the transmitter transmits a +1. If neither the k nor k + 1st level was transmitted, the transmitter repeats the correct level (this has several orders of magnitude less probability of occurrence).

Figure 9 shows the relative power savings as a function of the request for repeat. Notice that information feedback saves very little power as compared to decision feedback until the request for repeat exceeds 10%.

A more interesting aspect of this problem is currently under investigation. This is the transmission of 1 of M orthogonal signals. In this problem one is no longer "certain" that the transmitted signal is one of two possible signals, but one can choose L signals among which the true signal lies.

7. Distortion in Pulse Count FM Discriminators

A pulse count discriminator limits the incoming FM signal and then produces a pulse of uniform area and of a single polarity upon every Nth zero crossing of the incoming signal (N is an integer). In a common practical version of the device N=2, however, divide down versions exist in which N=10, 20, or some higher number.

Two questions arise in the use of such a detector. One concerns the trade off between pulse shape - sensitivity - distortion - bandwidth, and maximum allowable frequency deviation assuming that N=1.

The second question asks what degradation occurs if $N > 1$.

These questions have been answered by splitting the actual circuit into two conceptual parts. Figure 6A illustrates the basic circuit while Figure 6b illustrates the imagined breakup of the circuit into a combination of a circuit that produces an ideal impulse on every desired zero crossing and a linear network whose impulse response is the actual desired pulse shape.

One now calculates non-linear distortion limits for the impulse train and then passes the resultant signal through the frequency response of the linear network to obtain the total distortion.

This approach allows one to set arbitrary limits both upon the allowable non-linear distortion and upon the linear frequency distortion caused by using various different practical pulse shapes. It also allows one to calculate directly the restricting effects of increasing N, both from the non-linear and the linear frequency distortion viewpoints.

8. Wideband, Low Distortion FM Generator Using Digital Techniques

A theory has been developed showing that the alternate charging and discharging of a capacitor by signal controlled constant current generators will produce an ideal FM triangular signal. This triangular wave may be converted into a sinusoidal form using a non-memory diode shaping network so that wide deviations and/or high modulating frequencies may be handled without filter distortion problems.

A circuit has been constructed and operated with carrier frequencies between 1 hertz and 2 MHZ. At any carrier frequency, f_o, it was possible to obtain peak deviations for low modulation frequencies of 0.75 f_o before distortion terms exceeded 1%. (This limit was imposed by practical circuit limitations not by theoretical problems). If the deviations are restricted to 0.5 f_o then total harmonic distortion may be restricted to less than 0.2%.

With a circuit of this type it is possible to obtain a 500 KHZ deviation directly at a carrier frequency of 1 MHZ and then hetrodyne up to any desired carrier instead of the more normal situation of obtaining an initial very small deviation which must be multiplied by hundreds or thousands of times to obtain a final wide deviation.

Since the circuitry is essentially all of a digital form, it should lend itself to relatively easy integration.

9. Studies of a Foster Seely type discriminator

Pole-zero constructions for the networks driving a Foster Seely type FM detector have been made. From these the theoretical quasi-static distortions have been calculated as a function of deviation. This approach also yields results as to the effects of failure to balance the two halves of the circuit. The effects of varying circuit coupling and the relative sizes of primary and secondary resonance voltages are also easily studied from this viewpoint.

The pole-zero approach does not yield any bounds upon the transient response of the circuit. To find such bounds the circuit has been treated as an approximate differentiator in the time domain. With this approach one finds approximate bounds of $\mu_{max} \leq \frac{0.10w_o}{Q}$ and $\Delta w \leq \frac{0.10w_o}{Q}$ for low distortion. Under these conditions and if $\Delta w > \mu_{max}$ then the percentage second harmonic distortion is found to be 25 $Q(\Delta w/w_o)$. In such a circuit the detection sensitivity, assuming equal primary and half secondary voltages, E, is found to be $(2.8QE)/w_o$ hence one has the expected trade offs between allowable bandwidth from the distortion viewpoint and detection sensitivity.

An analog simulation of a portion of such a circuit has been made to investigate the applicability of these results to an "ideal" circuit.

10. <u>Interchannel intermodulation in FM multiplex transmitted via a randomly time dispersive channel</u>.

Experimental investigations are continuing to properly characterize interchannel intermodulation distortions in terms of channel parameters such as fading rate, spread and probability distribution of the time dispersion and such signal parameters as position within the band. An initial set of data has been plotted using a 4MHZ carrier and the PIB random channel simulator. These results agree with the general form of previously published, empirical results. Work is continuing, both to improve the instrumentation for the system and then to determine variations caused by the several interesting parameters.

11. <u>Frequency Locked Loop Investigations</u>

Experimental and theoretical investigations have been made of a possible new type of FM detector known as a frequency locked loop.

In this detector a feedback loop is connected around a Clarke-Hess discriminator as shown in Figure 11. This loop causes the tuning of the detector to track the incoming signal so that the normal detector output remains close to zero throughout the deviations of the carrier. By taking the system output beyond the loop amplifier the normal output swing for a given input deviation is obtained.

Although the threshold properties of the circuit do not appear to be as desirable as initial calculations had indicated they might be, the circuit does have good AM suppression characteristics above threshold and further investigation appears warranted.

Conclusions:

From 15 September 1965 to 15 March 1966, several important problems have been solved and many others are on their way to completion. It is estimated that - 1. Digital Communication With Information Feedback; 2. The Least Mean Square Estimator of a Fading FM Signal; 3. Error rates in FSK Transmission Using an FM Signal; 4. Distortion in Pulse Count Discriminators; 5. The Theory and Practical Implementation of a Wideband FM Generator, will be completed by 15 September 1966.

Projects which will extend beyond 15 September 1966 are -

1. A Comparison of the Output SNR & Threshold of the MLE and Least Mean Square Estimator, and the FM Discriminator, Phase Locked Loop and Frequency Demodulator Using Feedback.

2. The Operation of the Phase Locked Loop With Delay.

3. The Operation of the Phase Locked Loop in a Fading Environment.

4. The Use of a Phase Locked Loop in a Frequency Demodulator With Feedback.

5. An investigation of intermodulation effects of multiple access satellite communications using a TWT.

6. The detailed analysis of various FM discriminators.

7. The formulation of a suitable theory to predict interchannel intermodulation distortion for multichannel FM transmitted via a time varying channel.

8. The analysis and design of the frequency locked loop.

9. The comparison of various FM detectors under fading input signal conditions.

Several new projects are anticipated for the two year period beginning 15 September 1966. These include Synchronization of several Phase Locked Loops, a study of the synchronization problem with respect to the transmission of digital signals, the design of optimum and sub-optimum signals, and an investigation of realizeable signal detection schemes based on non-parametric statistical tests.

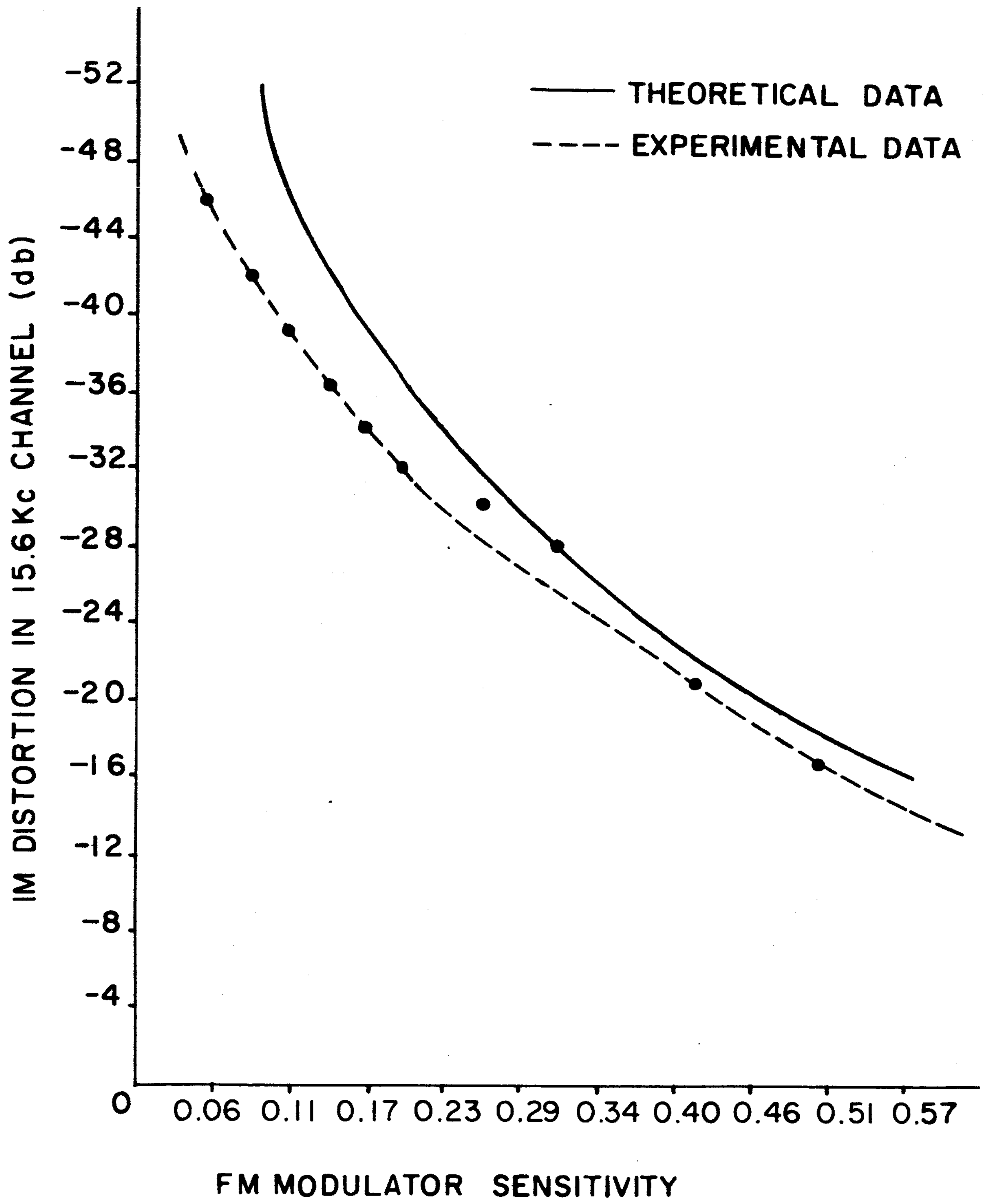


Fig. I IM Distortion vs. Normalized FM Deviation ($\frac{\Delta f}{\text{loop Gain}}$)

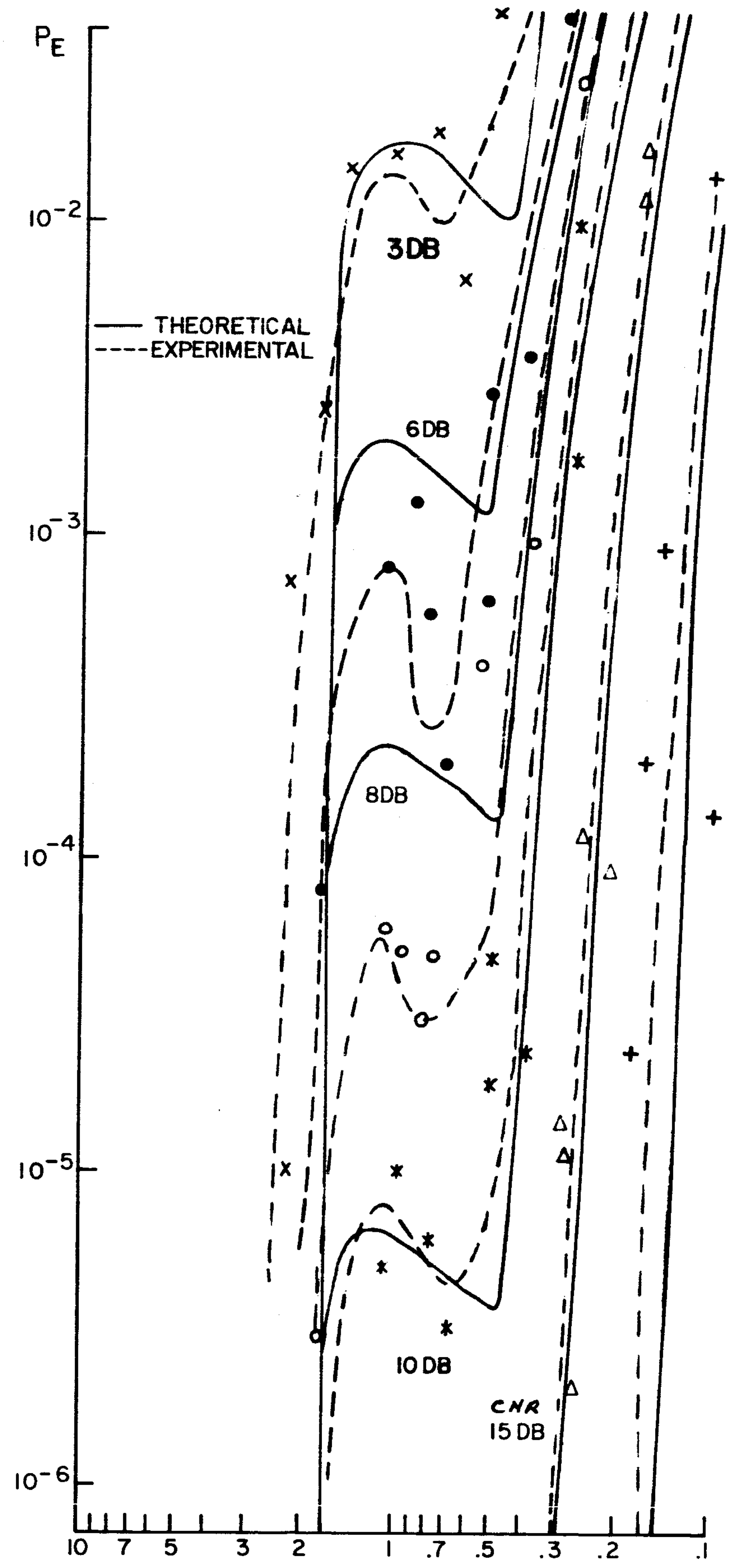
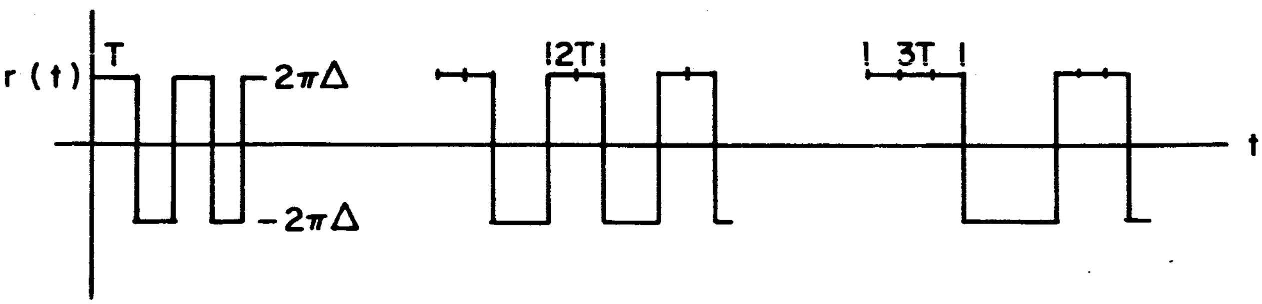
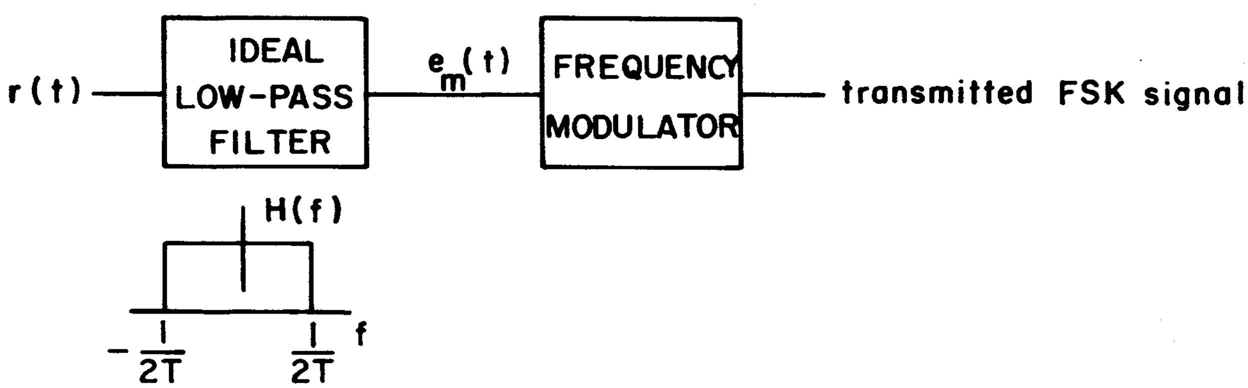


Fig. 4 FSK Digital Transmission Theoretical & Experimental Error Rates

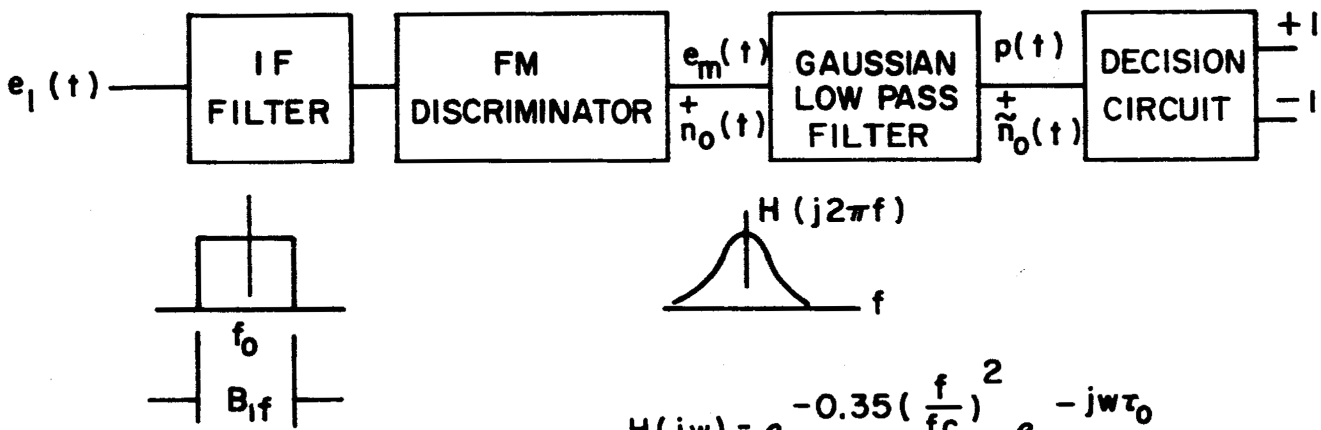


2a The Three Sequence Transmitted



2b The Filtering of the Data to be Transmitted

FIG. 2



$$H(jw) = e^{-0.35\left(\frac{f}{fc}\right)^2} e^{-jw\tau_0}$$

FIG. 3 The FM Discriminator

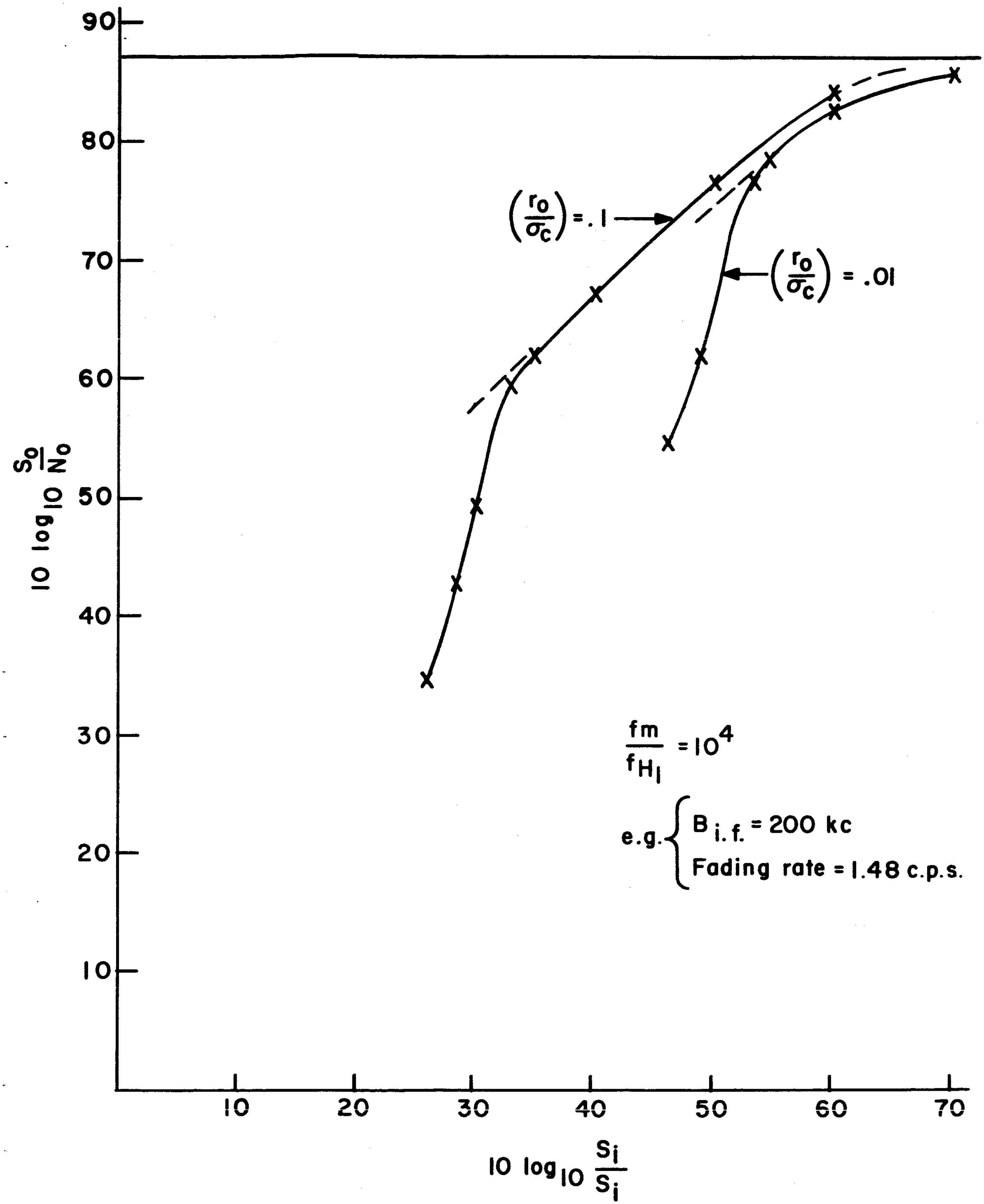


Fig. 5 FM Discriminator with a Fading Signal

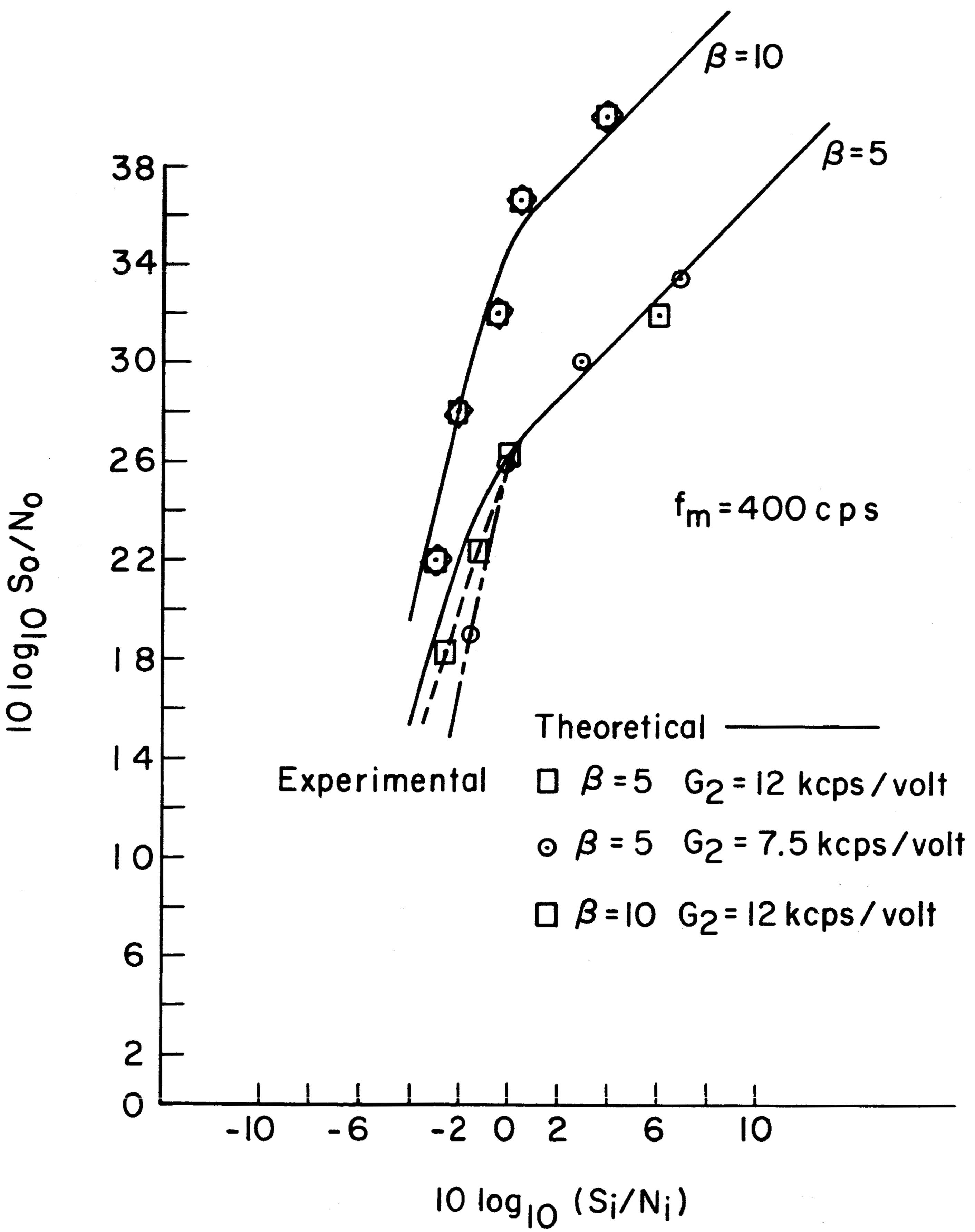


Fig. 6 Phase Lock Loop Characteristics

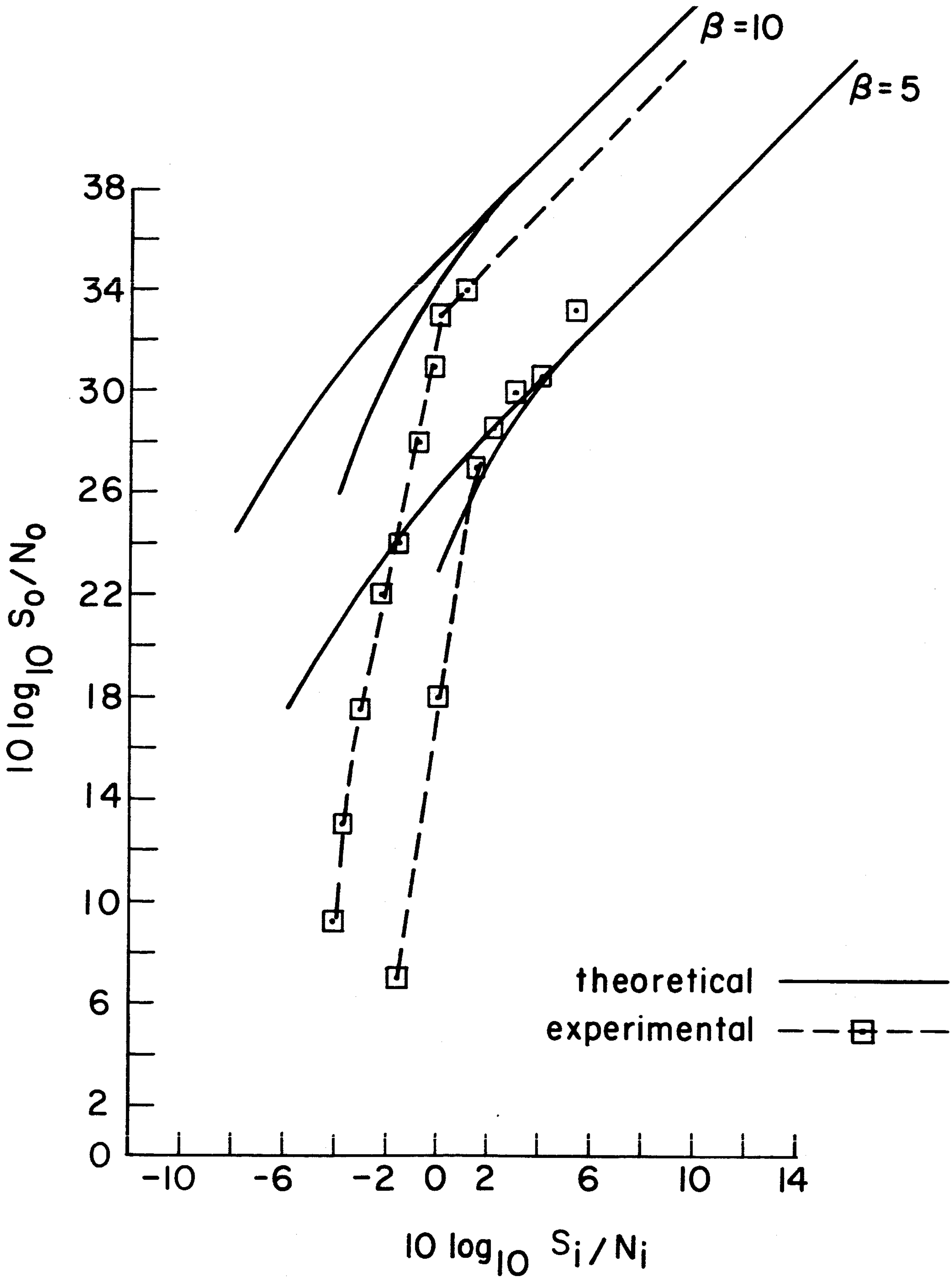


Fig. 7 FMFB Demodulator Characteristics

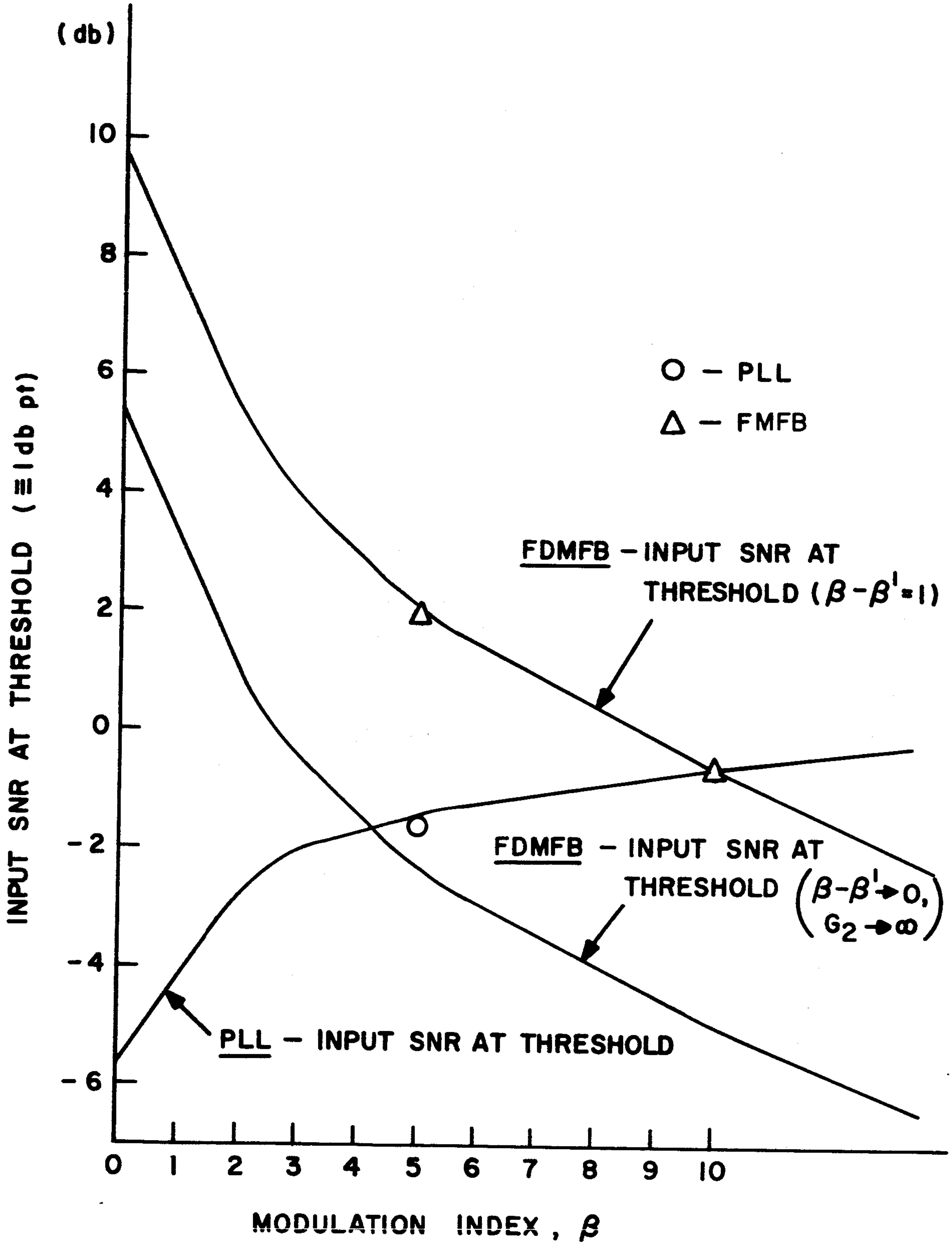


Fig. 8 Threshold Comparison of the PLL and the FMFB

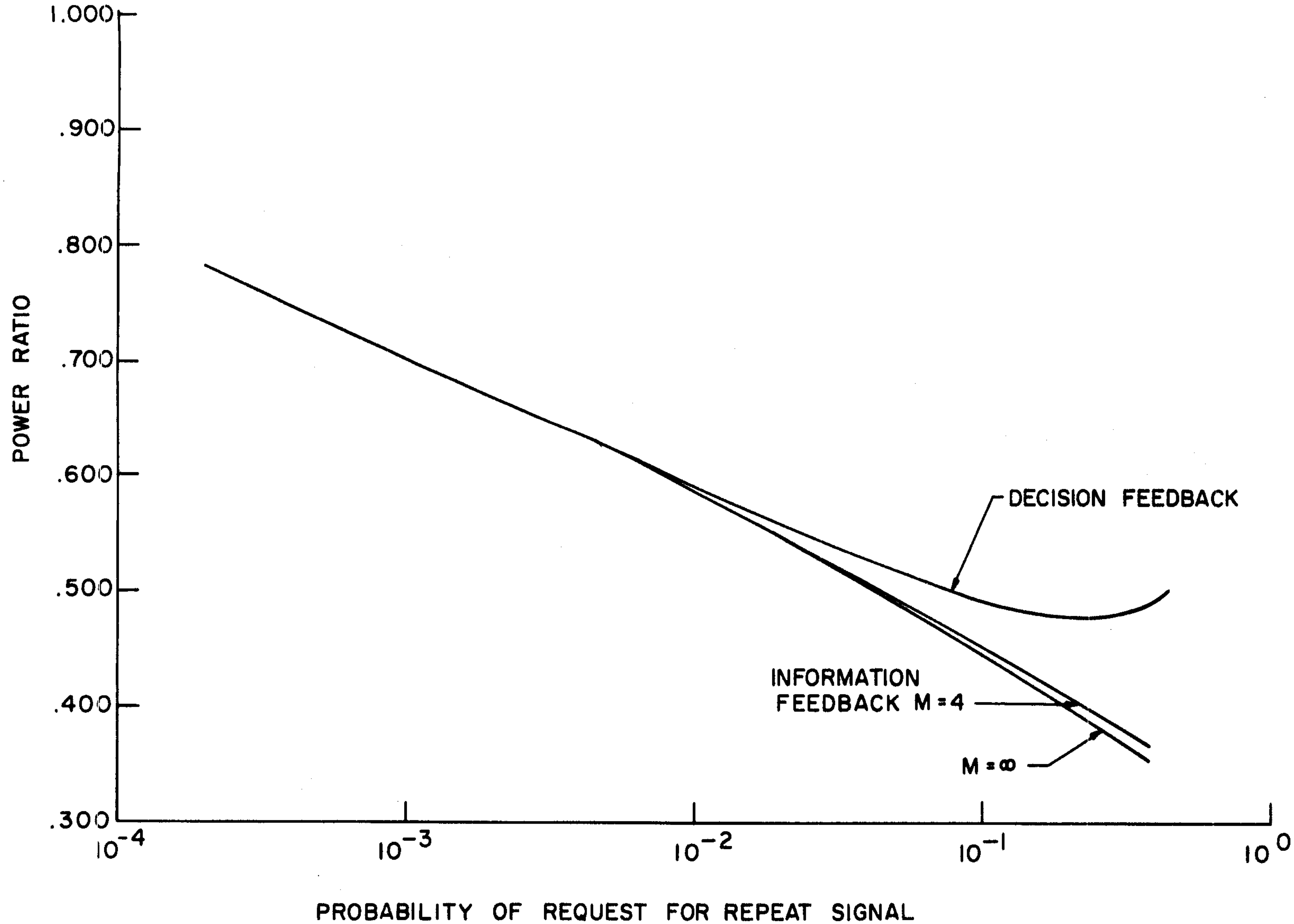


Fig. 9 Average Transmitter Power Ratio of A System With Feedback to a System without Feedback to maintain a Probability of Error equal to 10^{-6} as a function of the probability of a request for a repeat.

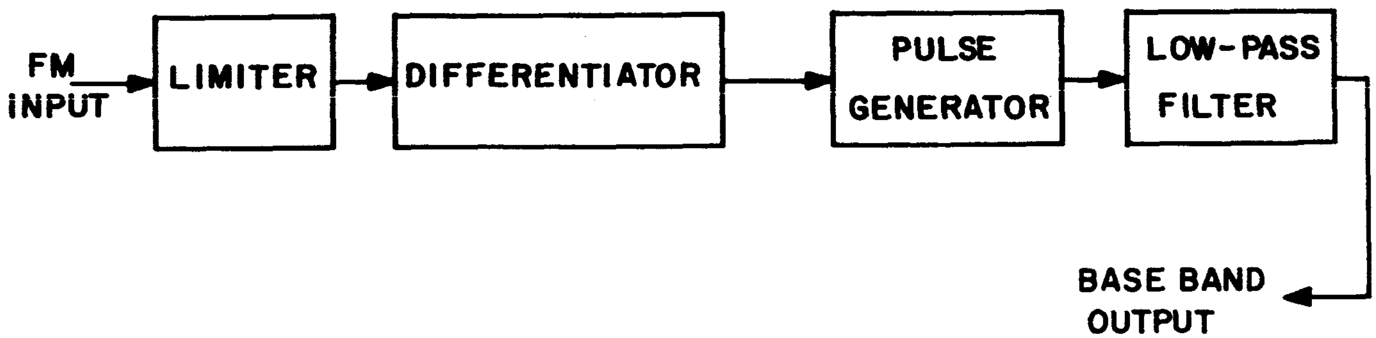


Fig. 10a Pulse Count Discriminator

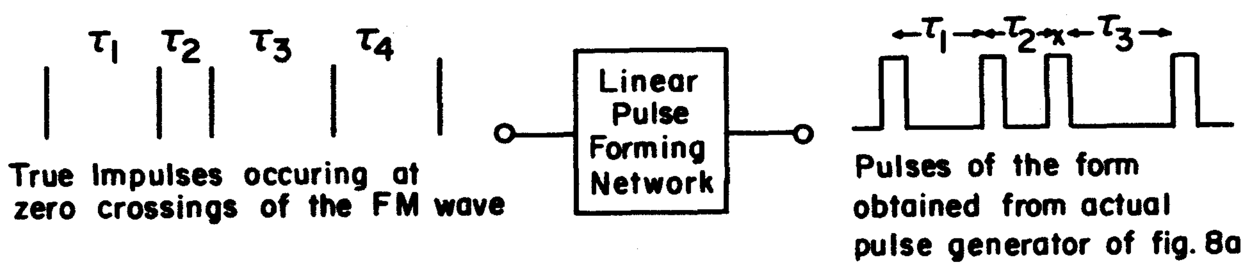


Fig. 10b Conceptual Form of Differentiator and Pulse Generator

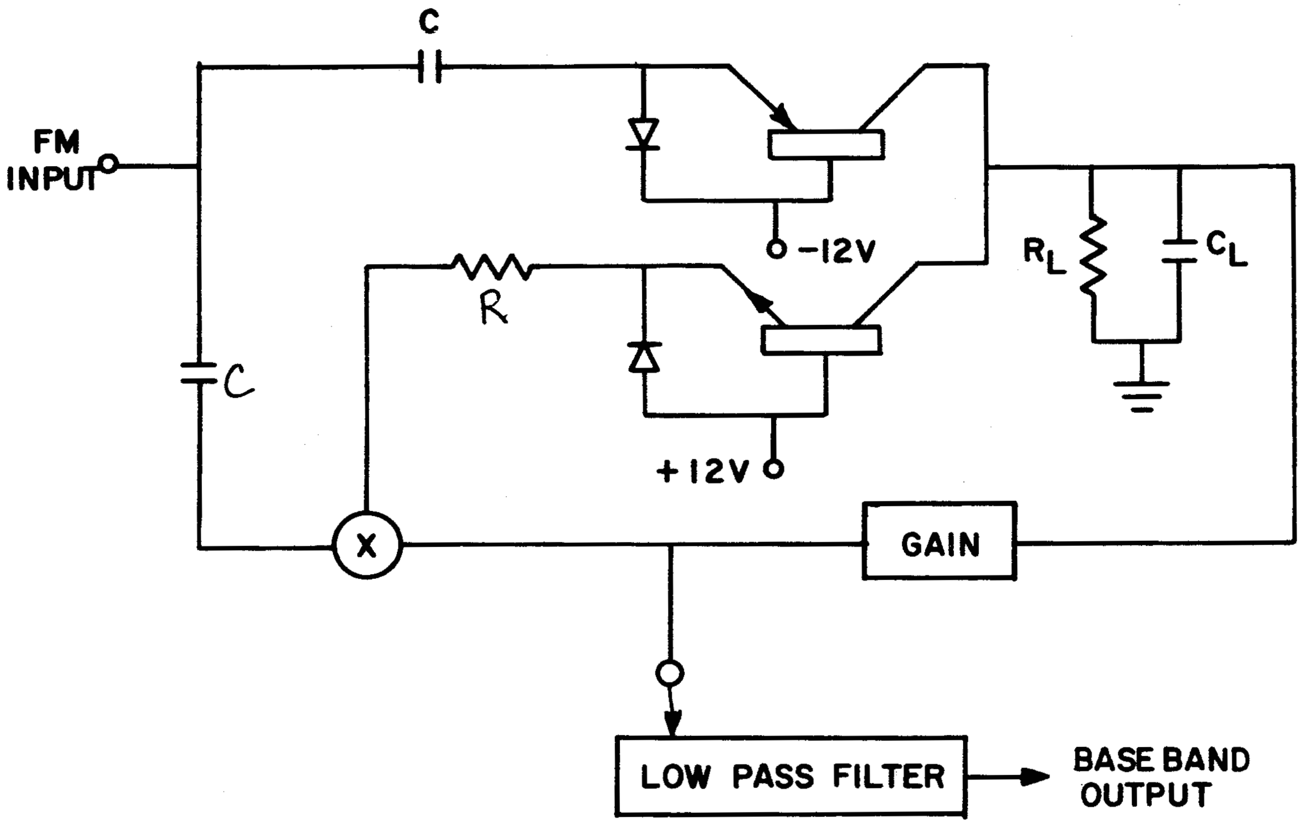


Fig. 11 Frequency Locked Loop